SIMULTANEOUS BUNCHING AND PRECOOLING MUON BEAMS WITH GAS-FILLED RF CAVITIES[*]

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Abstract

High-gradient, pressurized RF cavities are investigated as a means to improve the capture efficiency, to effect phase rotation to reduce momentum spread, and to reduce the angular divergence of a muon beam. Starting close to the pion production target to take advantage of the short incident proton bunch, a series of pressurized RF cavities imbedded in a strong solenoidal field is used to capture, cool, and bunch the muon beam. We discuss the anticipated improvements from this approach to the first stage of a muon cooling channel as well as the requirements of the RF cavities needed to provide high gradients while operating in intense magnetic and radiation fields.

INTRODUCTION

The most productive means of producing muons for intense muon beams is from pion decay, which requires pion production from proton interactions within a target. Such a production mechanism results in a muon beam which has such an enormous energy spread that some method of phase rotation is required to achieve the desired flux of muons into the acceptance of realistic downstream devices, such as an ionization cooling channel [1].

Two general techniques have been discussed for the phase rotation of such a beam: low frequency [2] and high frequency [3]. High frequency phase rotation requires a large number of RF cavities with varying frequency. Low frequency phase rotation requires much longer channels because of the limited gradient achievable by low-frequency cavities.

High-pressure, gas-filled RF cavities provide a possible means of overcoming the limited gradients that low-frequency RF can achieve. Recent tests performed at Fermilab suggest gradients in excess of three Kilpatrick [4], making it possible to design short, low-frequency phase rotation channels.

If the gas in the channel is not exceedingly dense, it will have little effect on the pion beam during its short lifetime. In addition, if the gas is low-Z, such as hydrogen or helium, the gas will act as an ionization cooling material for the muons. Thus, it may be possible to phase rotate a sufficient number of muons into a desired acceptance while simultaneously cooling the beam.

In this article, we explore the possibility of designing as low-frequency phase rotation scheme using high-pressure, gas-filled RF cavities.

PION PRODUCTION & CAPTURE

The initial beam has been generated using the MARS code [5], developed by Nikolai Mokhov at Fermilab and tested numerous times over its long and illustrious history. We simulated a 1 MW, 25 GeV, 1 ns proton pulse incident on a carbon rod target. The target is 80 cm long and 1.5 cm in diameter, tilted at an angle of 100 mrad with respect to the central axis of the channel in order to reduce pion recapture in the target. Aligned with the central axis of the channel is a 20 T solenoid spanning the length of the target. Such a target region has been discussed in great detail in the first and second Neutrino Factory feasibility studies [1,6].

Following the 20 T target region is a tapered solenoid, taking the beam adiabatically from 20 T at the target to 5 T at 15 m downstream from the target. Transport of the beam through such a taper increases the spot size of the beam from 15 cm in diameter at the target to 30 cm in diameter at the 15-m mark, matching the size of the beam designed for the Muons, Inc. helical cooling channel (HCC).

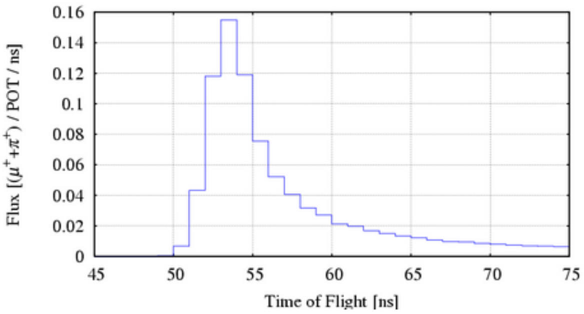

Figure 1: Time of flight distribution of positively charged pions and muons at 15 m downstream from the target.

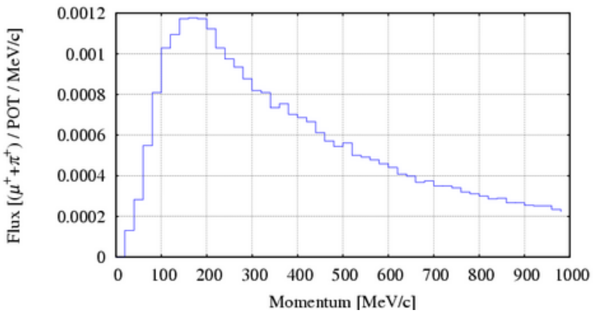

Figure 2: Momentum distribution of positively charged pions and muons at 15 m downstream from the target.

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The resulting beam is a mix of pions and muons, approximately 31% (25%) π^+ (π^-) and 21% (23%) μ^+ (μ^-). The positively charged content of the beam is shown in the time and momentum histograms depicted in Figures 1 and 2, respectively. From this point, we consider only the positively charged content in our analysis.

PHASE ROTATION

To maintain the beam, we consider series of 5 T solenoids of 10 cm in length with a center-to-center spacing of 25 cm. In the 15 cm gap between the solenoid coils, we place 10 cm long RF cavities, leaving 2.5 cm spacing between elements. This lattice was implemented in G4Beamline, a beam transport code based on the GEANT4 Toolkit, developed and maintained by Tom Roberts [7].

The first 20 m of RF—starting immediately after the 15 m tapered solenoid—is the low-frequency phase rotator, containing 80 25MHz RF cavities. We assuming 25 MV/m in each cavity and an RF phase of zero. To attain the large gradient at such low frequencies, we assume the cavities are filled with 100 atm hydrogen gas. Under these conditions, gradients of more than three Kilpatrick have been achieved at Fermilab, and assuming such cavities scale with square-root of the frequency, a gradient of 25 MV/m in each cavity should be achievable.

We attempt to achieve a beam that can be injected into a helical cooling channel (HCC) with an aperture of 30 cm, similar to those simulated by Muons, Inc. [8]. Simulations of the HCC suggest a large acceptance, allowing a beam with a momentum spread of ±25% [9]. We attempt to match into a channel with a central momentum of 335 MeV/c, thus allowing an acceptable momentum range from approximately 250 MeV/c to 420 MeV/c. We also assume this HCC uses 400 MHz RF to maintain longitudinal stability. Thus, we examine the ability of the 20 m phase rotation channel to rotate positively charged pions and muons in the 250-420 MeV/c momentum band.

Following the phase rotation section, a 30 m section (120 RF cavities) of RF is designed to adiabatically capture the rotated beam into 400 MHz RF buckets. Over these 30 m, the gradient is linearly ramped from 0 MV/m to 30 MV/m, easily achieved with gas-filled cavities at 400 MHz. The synchronous phase of each cavity is set to 6.3° to provide an average accelerating gradient of 3.3 MV/m, compensating for energy loss in the 100 atm gas.

Following capture, we transport the beam for 15 m (60 RF cavities) at 400 MHz and 30 MV/m to a total distance of 80 m from the end of the target. This last section is not necessary and is used only to show that the beam is maintained.

Figure 3 shows the transmission of positively charged muons in the 250-420 MeV/c acceptable momentum band at various distances downstream from the 15 m tapered solenoid. For comparison, we show the transmission for the same beam in a normal decay channel without RF (only 5 T solenoids). The rise in the transmission without RF comes from the decay of higher-momentum pions into the acceptable momentum band. However, one can see that the phase rotator moves a significant number of muons and pions into the desired momentum band, and maintains them at 400 MHz. The resulting yield at the 80-m mark is approximately 0.24 μ^+ / proton-on-target (POT), comparable to the yield after the high-frequency phase rotator used in the neutrino factory feasibility study 2a [10], assuming a similar carbon target (instead of a mercury jet discussed in the feasibility study).

The bunching of the beam into 400 MHz results in a bunch train of approximately 10 well-formed bunches. No attempt to assemble these bunches into a single bunch has been made.

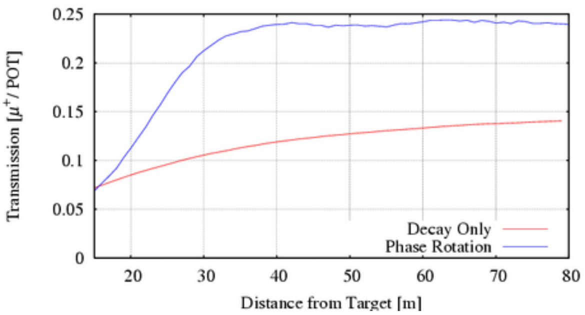

Figure 3: Transmission of positive muons in the 250-420 MeV/c momentum range from 15 m to 80 m downstream from the target. The blue curve shows the transmission with phase rotation and matching into 400 MHz RF. The red curve shows the transmission of a similar beam without RF.

IONIZATION COOLING

The high-pressure hydrogen gas in the RF cavities will simultaneously provide ionization cooling for the muons and strongly interact with the pions. At room temperature and 100 atm, hydrogen gas has a nuclear interaction length of $\lambda_I = 59.4$ m, much longer than the length scale associated with pion decay, $c\tau_\pi = 7.4$ m. Thus, we suspect the losses due to strong interactions with the gas to be small.

Similarly, we expect the ionization cooling to be relatively small as well, but since the muons traverse the entire length of the channel, the effect will be cumulative. The average energy deposited into the gas from a 335 MeV/c muon traveling the length of the 65 m channel following the taper (consisting of 260 10 cm RF cavities) is 86 MeV, approximately 35% of the muon's kinetic energy. Thus, we expect an ionization cooling effect of the same order of magnitude. However, since there is no dispersion and our acceptable momentum spread lies near the minimum of the Bethe-Bloch curve, we expect the cooling to be only in the transverse dimensions.

The transverse emittance of the positive muons is plotted down the length of the 65 m channel following the tapered solenoid in Figure 4. The emittance is calculated by ECALC9, a tool developed for muon ionization cooling simulations and a part of the ICOOL simulation package [11]. Again, we show the emittance with the RF (and, therefore, without gas) and see that it remains constant as expected. Over the length of the 65 m section of RF, we see an approximately 18% cooling effect in the transverse plane.

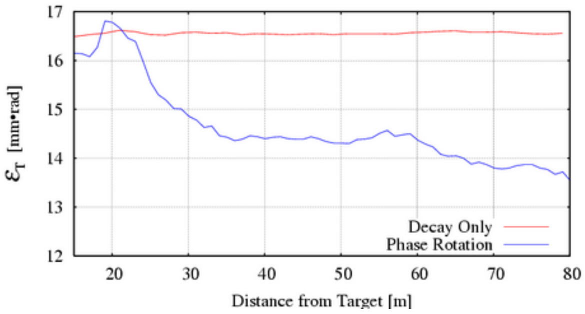

Figure 4: Transverse emittance of the positive muons in the channel downstream from the tapered solenoid. The blue shows the ionization cooling effects due to the gas-filled RF cavities. The red shows the constant emittance of a conventional decay channel without RF an gas.

FUTURE CONSIDERATIONS

Figure 3 shows that the capture into 400 MHz RF buckets is very efficient, but the resulting bunch structure is not desirable for a muon collider. Neutrino factories, that only require large muon flux do not need to accumulate the muons into a single bunch, but a muon collider will need a single bunch. The ~10 bunches that result from the 400 MHz buncher may need to be unified in order for this scheme to be useful for muon colliders.

Additionally, we have assumed that a basic HCC will follow this channel. No matching has been considered for such a device other than the acceptable momentum band of 250-420 MeV/c that such an HCC should have. A more thorough matching analysis will be required if this scenario is to be useful.

Alternate lattices exist for this channel as well. Since we have considered matching into an HCC, it may be possible to construct a helical decay channel (HDC) that will more easily match into the HCC. To make room for the low-frequency RF, however, the HDC may need to be "discretized" by using conventional bending magnets assembled in a piece-wise linear helix. Such a device may have a smaller acceptance than a conventional HCC, but it may also work as matching section from a straight solenoid into an HCC.

High frequency phase rotation and bunching will also be attempted with gas-filled RF cavities in future simulations. A comparison between models can then be done to choose the most viable option for a neutrino factory or muon collider.

While this work is preliminary, it shows that using high-pressure, gas-filled RF can make low-frequency phase rotation possible over a short distance. Such a technique is highly desirable for neutrino factories, muon colliders, and any other possible use of intense muon beams.

REFERENCES

[1] T. Anderson et al., (Eds. N. Holtkamp and D. Finley), "A Feasibility Study of a Neutrino Source based on a Muon Storage Ring," April 15, 2000. http://www.fnal.gov/projects/muon_collider/nu/study/report/machine_report/

[2] R. Fernow, "Phase rotation for the muon collider," MUC-NOTE-302, 2004. http://www-mucool.fnal.gov/notes/noteSelMin.html

[3] D. Neuffer, "Exploration of the high-frequency buncher concept," MUC-NOTE-269, 2003. http://www-mucool.fnal.gov/notes/noteSelMin.html

[4] R. E Hartline, R. P. Johnson, M. Kuchnir, C. M. Ankenbrandt, A. Moretti, M. Popovic, D. M. Kaplan, K. Yonehara, "Mark II High-Pressure RF Test Cell Measurements with Molybdenum Electrodes at Lab G," MUC-NOTE-285, 2004. http://www-mucool.fnal.gov/notes/noteSelMin.html

[5] N.V. Mokhov, "The Mars Code System User's Guide", Fermilab-FN-628 (1995); O.E. Krivosheev, N.V. Mokhov, "MARS Code Status", Proc. Monte Carlo 2000 Conf., p. 943, Lisbon, October 23-26, 2000; Fermilab-Conf-00/181 (2000); N.V. Mokhov, "Status of MARS Code", Fermilab-Conf-03/053 (2003); N.V. Mokhov, K.K. Gudima, C.C. James et al, "Recent Enhancements to the MARS15 Code", Fermilab-Conf-04/053 (2004). http://www-ap.fnal.gov/MARS/

[6] S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, ed., "Feasibility Study-II of a Muon-Based Neutrino Source," BNL-52623 (2001).

[7] T. Roberts, G4Beamline. http://www.muonsinc.com/g4beamline.html

[8] Y. S. Derbenev, R. P. Johnson, "Six-dimensional muon beam cooling using a homogeneous absorber," MUC-NOTE-284, 2004. http://www-mucool.fnal.gov/notes/noteSelMin.html

[9] K. Yonehara, D. Kaplan, K. Beard, S.A. Bogacz, Y. Derbenev, R.P. Johnson, K. Paul, T.J. Roberts, "Simulations of a Gas-Filled Helical Muon Beam Cooling Channel," submitted as PAC05 proceeding.

[10] J.C. Gallardo, J.S. Berg, R.C. Fernow, H. Kirk, R.B. Palmer, D. Neuffer, K. Paul, "New and Efficient Neutrino Factory front-end Design," MUC-NOTE-316, 2005. http://www-mucool.fnal.gov/notes/noteSelMin.html

[11] R. Fernow, "Physics analysis performed by ECALC9," MUC-NOTE-280, 2003. http://www-mucool.fnal.gov/notes/noteSelMin.html

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